# SAFETY EVALUATION OF LANE CHANGE COLLISION AVOIDANCE SYSTEMS USING THE NATIONAL ADVANCED DRIVING SIMULATOR

**Alrik L. Svenson**

National Highway Traffic Safety Administration

**Valerie J. Gawron**

General Dynamics

**Timothy Brown**

National Advanced Driving Simulator

United States of America

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## ABSTRACT

This paper reports on the status of the evaluation of several lane change collision avoidance systems (CAS) types using the National Advanced Driving Simulator (NADS). The goal of this evaluation is to examine driver behavior with a variety of lane change CAS to determine what leads to the safest driver behavior, and to investigate if the use of a lane change CAS with only a proximity warning system (i.e., blind spot detector) provides sufficient warning to drivers. The study begins with a comprehensive review of literature in this area. Then, simulator test scenarios are developed for the NADS to examine and compare five lane change CAS types, namely a representative commercially available proximity warning system, the TRW proximity only CAS, the TRW comprehensive system, a nonplanar mirror on the left (driver's) side of the vehicle, and a baseline with standard passenger vehicle mirrors. The test scenarios are based on Sen, Smith, and Najm [1] lane change crash data analysis. Preliminary results on the driver's acceptance of the lane change CAS and decision to use CAS information in making lane change decisions are presented. This research is still in progress and is planned to be completed in mid 2005.

## INTRODUCTION

Lane change collision avoidance systems (CAS) are designed to prevent crashes in lane change maneuvers by alerting the driver to hazards in the adjacent lanes of traffic. From previous studies, it has been determined that many crashes during a lane change occur when drivers are unaware of hazards around their vehicle. A CAS can detect surrounding vehicles that are in zones on the sides and behind the vehicle and notify the driver through the use of a warning signal such as an auditory message or a visual symbol in the side or rear view mirrors. Lane change crashes account for approximately 5 percent of the total of all reported crashes in the General Estimates System (GES) data. To the extent that a CAS helps drivers avoid unsafe lane changes, it has the potential to reduce crashes.

The Space and Electronics Group of TRW has developed a CAS consisting of two detection and warning subsystems [2]. The first subsystem, a proximity warning subsystem, detects vehicles in a defined proximity zone on the side of the vehicle including the region referred to as the blind spot. The second subsystem, the fast approach subsystem, detects vehicles further behind the vehicle than the proximity zone that are at high closing speeds approaching the proximity zone.

## LANE CHANGE CAS

Five types of lane change CAS were tested: 1) TRW proximity only system, 2) TRW proximity and fast approach system, 3) commercially available proximity warning system, 4) nonplanar mirror (left side), and 5) baseline (standard left and right side mirror).

### TRW Proximity Only System

The first lane change CAS is TRW's Space and Electronics Group proximity-warning subsystem that detects vehicles in a defined proximity zone on the side of the vehicle including the region referred to as the blind spot. The proximity zone, also known as the keep-out zone, is adjacent to and 30 feet behind the vehicle [3]. The system does not warn drivers about stationary objects but does monitor vehicles in the blind spot. A red triangle appears right in the field of view in the rearview and side-view mirrors when another vehicle is in a vehicle's path (see Figure 1). This CAS has been designed to warn drivers about vehicles not in the mirror, i.e., in the blind spot. The red triangle has been also used in the Buick XP2000 concept car [4]. The display associated with this system simulation in NADS is presented in Figure 2 for driver's side mirror and Figure 3 for the passenger side mirror.

**Figure 1. TRW view from driver's seat of warning icons in and next to mirrors [2].**

**Figure 2. View from driver's seat of TRW CAS simulation in NADS.**

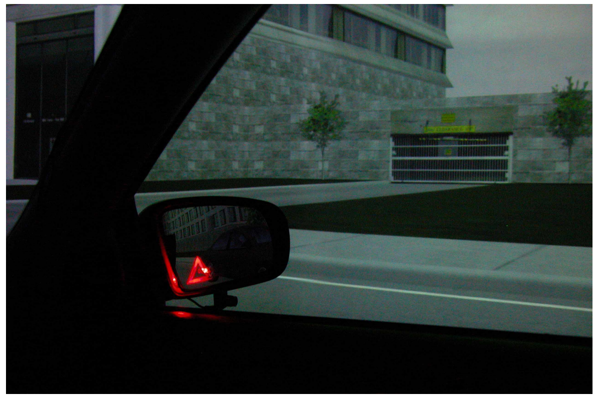

**Figure 3. View from driver's seat of passenger's side mirror of TRW CAS simulation in NADS.**

**TRW Proximity and Fast Approach System**

TRW also developed a fast approach subsystem, which detects vehicles further behind the vehicle than the proximity zone that are at high closing speeds approaching the proximity zone. Specifically, this system has a three second time to arrival into the proximity zone for fast approaching vehicles [3]. This second TRW system comes packaged with the proximity warning system in an integrated package. This CAS has been designed to overcome driver's inability to accurately perceive closing times. This system has a maximum relative velocity detection limit of 50 km/h (31.07 mph).

**Limited Proximity Warning System**

The third lane change CAS tested is a limited proximity warning system (LPWS). The LPWS system is mounted on the side mirrors and flashes when it detects an obstacle in the blind spot (see Figure 4 for both versions 1 and 2). The detection fields of view are arranged so that the tires of the vehicle in the blind spots are detected (see Figure 5). This typically covers an area approximately 3.5 to 4.2 m (12 to 14 ft.) to the side and up to 7.6 m (25 ft.) back from the external side view mirrors. The LPWS uses signal to noise processing methodologies of two sensors to measure the same field of view at two points in time. The system is operational when the vehicle is traveling at 20 or more mph. LPWS's sensor enables the detection of an object that is stationary or moving relative to the sensor but moving with respect to the background (or road surface). It can detect over one or more lane widths and back from the side view mirrors 8 to 20 meters (24 to 66 ft.) or further (using different lenses). It detects other vehicles with relative velocities of 0 to 64 km/h (40 mph). Over 10,000 units have already been sold. The display automatically adjusts to lighting conditions and works in all weather. This CAS has been designed to warn drivers about vehicles that are close but not in the mirrors (like the TRW Proximity Only System), vehicles with high closing speeds (like the TRW Proximity and Fast Approach System), and potential hazards not seen (such as stationary objects in the adjacent lane). The LPWS warns of a vehicle entering the blind spot under the following circumstances: 1) the participant automobile overtaking another automobile, 2) another automobile entering from the rear of the blind spot in the adjacent lane, and 3) another automobile entering laterally from the second lane over. These algorithms have been included in the NADS simulation. The display associated with this system simulation in NADS is presented in Figure 6. The triangular symbol is lit when it is unsafe to change lanes.

**Figure 4. LPWS side mirror display [showing version 1 (top) and version 2 (bottom)].**

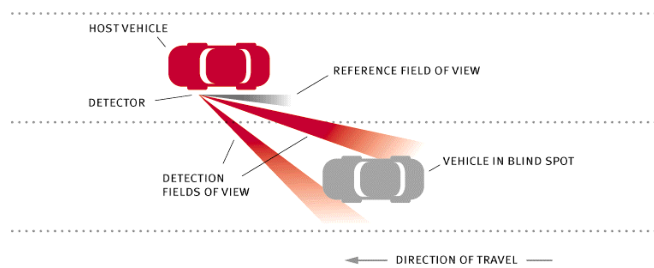


**Figure 5. LPWS blind spot detection (note: warnings are provided for blind spots on both sides of the test vehicle).**

**Figure 6. View from driver's seat of LPWS CAS simulation in NADS (same as TRW systems).**

### NonPlanar Left-Side Mirror

A fourth lane change CAS is a nonplanar mirror attached to the left side of the vehicle. The fields of view for both the right and left side mirrors are those illustrated in Figure 7. The implementation in NADS is presented in Figure 8. A spherical convex mirror with 1400 mm (55.1 in) radius of curvature on the passenger side has been used in this study. The radius of curvature is the common radius [5]. This is the low-cost proposed solution for blind spot collisions. Performance can be compared against the baseline to determine safety benefit and against the CAS to determine cost effectiveness.

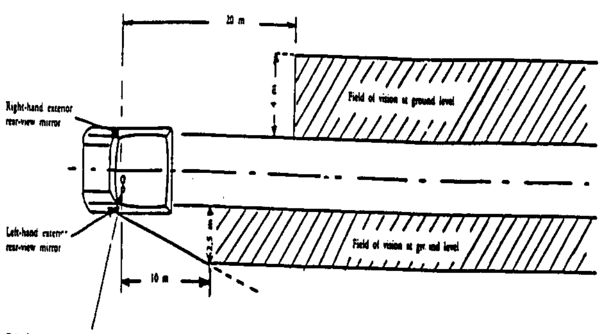


**Figure 7. Required field of view main exterior rearview mirrors [5].**

**Figure 8. View from driver's seat of convex mirror in NADS.**

### Baseline (Standard Side Mirrors)

This is the baseline against which the performance of all the lane change CASs are being compared. This is critical in determining the benefit of each CAS. The baseline is standard U.S. vehicle mirrors: planar on the driver's side, and a standard convex passenger side mirror.

## SIMULATED LANE CHANGE CONDITIONS

The lane change scenarios occur on nonjunction segments of roadway without traffic control with 50 mph speed limits. The status of the blind spot, the actions of the lead vehicle(s), and the direction of lane change defined the lane change scenarios. All three blind spot conditions have been combined with both sets of lead vehicle actions (described in the next section) and both left and right lane changes.

### Blind Spot Status

There are three possible conditions of the blind spot. In the first, there is no vehicle in the blind spot. In the second, there is a vehicle in the blind spot and it is traveling at the same speed as the test vehicle. In the third, there is a fast approaching vehicle in the blind spot and it is traveling at speed 30 mph (48 km/h) greater speed than the test vehicle. It is timed to be in conflict with the test vehicle during the lane change. This third condition for the blind spot status occurs only in the last trial. This limitation has been imposed in keeping with estimates for the frequency of occurrence of fast approach vehicles since no on road or simulator data are available for actual driver behavior. These estimates are based on naturalistic driving data collected in Virginia by Olsen and Lee. Specifically, naturalistic lane change data were reviewed [6,7] to see how many cases fit the fast approach criteria. Their data included 8,677 lane changes (including some that were full passing maneuvers). They chose 500 lane changes for in-depth review. The 500 chosen for further analysis included all of the more severe and urgent cases (the fast approach criteria would definitely have been classified as a severe case and thus all cases fitting these criteria would have been included in the 500 lane changes analyses). There were 16 drivers who drove the instrumented vehicles for 20 days each (10 days in the sedan and 10 days in the Sport Utility Vehicle (SUV)). These drivers logged almost 25,000 miles in the course of the study. Drivers commuted in interstates and US highways in southwest Virginia (commutes of at least 40 km (25 mi.) each way). In the 500 cases, there was only one case in which a vehicle was approaching at >30 mph in the adjacent lane during the lane change (so this means 1 out of 8,776 lane changes). Olsen and Lee were unable to distinguish cases in which a driver was just considering making a lane change, checked the side mirror, saw a fast approaching vehicle, and decided to wait. For all of the lane changes, there was at least some lateral movement observed. Related data are available in reference [2]. These authors collected passing speed data from highway driving in Southern California.

In a recent study, Smith, Glassco, Chang, and Cohen [8] tested metrics defining last-second lane-change characteristics against data collected on a closed course, on the road, and in a simulator. The closed course data were collected as part of the Crash Avoidance Metrics Partnership (CAMP) between General Motors and Ford. The scenarios are more fully described in reference [9]. Drivers approached a stopped lead vehicle, a lead vehicle moving at a constant slower speed, or followed a decelerating lead vehicle. They were asked to either pass the lead vehicle "at the last second they normally would to go around a target representing a vehicle in the adjacent lane" or "at the last second they possibly could to avoid colliding with the target".

The above data were used to design simulation scenarios. In addition, the closing speed has been pre-tested to ensure that the drivers are able to perceive that the vehicle is indeed closing and not staying at the same distance. Also, on-road pre-testing has identified that high profile vehicles in the rear of the test vehicle can occlude the view of the fast approaching vehicle. Therefore, no trucks, busses, or SUVs have been included in the simulated traffic.

**Simulated Lead Vehicle Actions**

There are two sets of lead vehicle actions as summarized below.

**Lead Vehicle Braking**

The vehicle ahead in the same lane as the test vehicle slows to a distance 50% of the CAMP drivers selected as the hard steering distance to a stopped vehicle. Pre-testing was used to determine the timing to ensure that the stimulus for initiating a lane change is similar across.

**Uncovered Slower Lead Vehicle**

The vehicle ahead in the same lane as the subject vehicle makes a lane change to the adjacent lane and reveals (uncovers to the driver's view ahead) a slower lead vehicle when the test vehicle is at the distance 50% of the CAMP drivers selected as the hard steering distance to a slower moving vehicle (driver at 60 mph and slower lead vehicle at 30 mph). Again, pre-testing was used to determine the timing to ensure that the stimulus for initiating a lane change in the simulator is as similar to collected test data as possible.

Several outcomes to these lead vehicle actions are possible. In the event that the participant comes to a stop, traffic in the adjacent lane continues to flow by until the lane is cleared. In this case, the participant was asked by the researcher to go around the vehicle in front when the lane clears. If the participant does not change lanes, the slowing/stopped vehicle turns off the roadway. In the event that the participant waits for the lane to clear, the vehicle in the participant's blind spot moves past the participant thereby clearing the lane and enabling the participant to complete the lane change.

**Lane Change Direction**

The direction of the lane change is based on the participant making successful left and right lane changes in response to the lead vehicle actions. Participants are given instructions to change lanes when forced by traffic conditions and to stay in the new lane until forced again by traffic. Lane changes have been in either the right or the left direction. The active lane-change CASs provide similar warnings for either direction. The test convex mirror is mounted only on the left side. The baseline has standard U.S. vehicle mirrors: planar on the driver's side, and a standard convex passenger side mirror.

## EXPERIMENTAL DESIGN

The experiment is a split plot (i.e., combination between and within subject design). The between subjects independent variables are age and CAS. There are two levels of age based on crash data and the NHTSA Research Goals: 16-21 years old, and > 65 years old. Subjects must have valid driver's licenses and were all recruited from the vicinity of Iowa City or Cedar Rapids, Iowa. All must meet NADS medical requirements. Subjects are paid $10 per hour for their participation. In addition, all subjects were selected for visual acuity, color vision, and contrast detection in the normal range. This criterion is based on work by Johnston, Cole, Jacobs, and Gibson [10]. There are four CAS systems to be compared to the baseline: TRW proximity (TRW), TRW proximity and fast approach (TRWF), LPWS, and convex mirror. There are 4 participants per age by CAS condition. Each participant has driven baseline and one of the four CASs. The within subjects variables have been trial, blind spot status, lead vehicle actions, and lane change direction.

Trial 1 is a baseline and is used for comparison against the four remaining trials of CAS (trials 2-5). All other independent variables (e.g., where forcing events occur) will be random with equal occurrences across subjects. To decrease predictability of events, each trial will begin at a different point in the driving database.

The remaining trials vary from 2 through 5 for the four CAS systems to be evaluated. Blind spot status is no vehicle in the blind spot (no), vehicle in the blind spot moving at the same speed as the test vehicle (same), or vehicle in the blind spot moving at 30 mph greater speed than the test vehicle (fast). Since this last blind spot condition occurs in less than 10% of lane changes (engineering estimate since no on-road crash data are available for this specific case), the fast approach vehicle is a threat only during this last trial (trial 5). Lead vehicle actions include lead vehicle brakes (brakes) and slow lead vehicle uncovered (uncovered). Lane change direction is left or right.

## NADS

The NADS is located at the University of Iowa's Oakdale Campus. It consists of a 24-foot dome in which an entire car, SUV, or truck cab can be mounted. All participants use the same vehicle, a passenger automobile (Chevrolet Malibu). The vehicle cabs are equipped electronically and mechanically using instrumentation specific to their make and model. At the same time, the motion system, on which the dome is mounted, provides 400 square meters of horizontal and longitudinal travel and ±330 degrees of rotation. The driver feels acceleration, braking, and steering cues as if he or she were actually driving a real vehicle. Each of the three front projectors has a resolution of 1600 x 1200; the five rear projectors 1024 x 768. The edge blending between projectors is 5 degrees horizontal. To enhance the resolution of the side and rear view mirrors, a 63-inch plasma panel has been mounted on the rear bumper to provide higher resolution images to the driver side, rear, and passenger side mirrors. The panel resolution is 1366 x 768.

## DATA COLLECTION SOURCES, TIMING, REDUCTION, AND "QUICK LOOK" VERIFICATION

There are four data collection sources: lane change characteristics and crash severity and pre-crash behavior from the NADS digital data, video, eye tracking over –60 to +170 degrees field of view with accuracy of one degree and 30 Hz update rate, and interview and questionnaire data. All digital data have been recorded at 120 or 240 Hz. Video is at 60 Hz. These sampling frequencies are based on previous driving simulator research.

## PRELIMINARY RESULTS

Sample driver responses to lane change scenarios are presented in Figures 9 through 15. On the plots of the steering wheel angle, a vertical dashed line indicates a lane change left (line points upward) or right (line points downward). A solid line indicates a crash occurred. One of the most common responses to the events is the driver braking in response to the action of the lead vehicle. Figure 9 illustrates a typical driver response to a braking lead vehicle. As can be seen from the figure, the participant applies the brake at a moderate level, thus allowing the vehicle in the blind spot to drive past and then changes lanes once the right lane is clear. Figure 10 illustrates a typical response to an uncovered slower moving lead vehicle. As can be seen in the figure, the driver applies the brakes slightly to slow down, and changes lanes once the adjacent lane is clear.

Another typical response to the event would be for the driver to slow down without changing lanes. This type of response was more common for an uncovered slow moving vehicle than for a braking lead vehicle. A typical response of this type is illustrated in Figure 11.

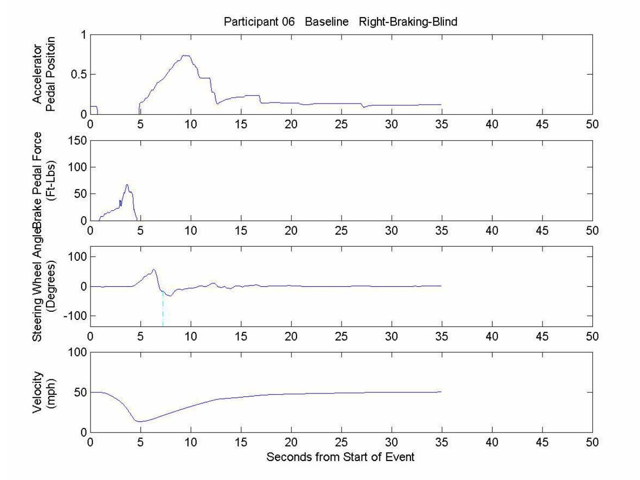


**Figure 9. Driver response to a braking lead vehicle in the form of braking followed by a slow speed lane change to the right.**

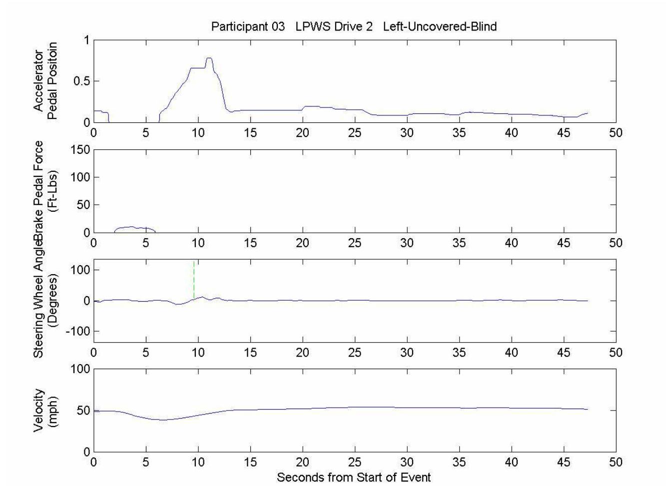


**Figure 10. Driver response to an uncovered slow moving lead vehicle in the form of slight braking followed by a lane change to the left.**

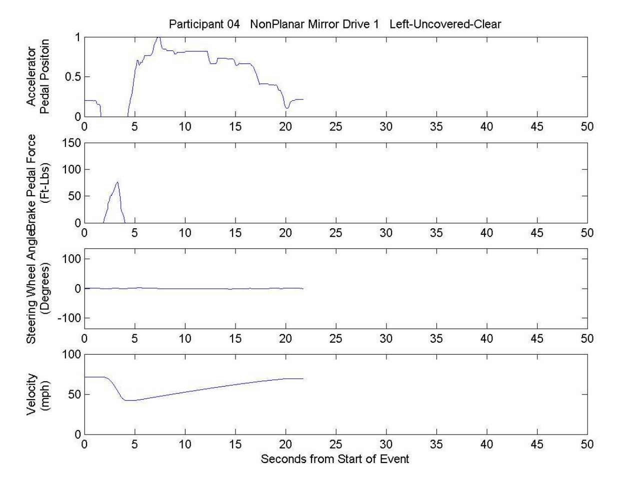


**Figure 11. Driver response to an uncovered slow moving lead vehicle in the form of braking without changing lanes.**

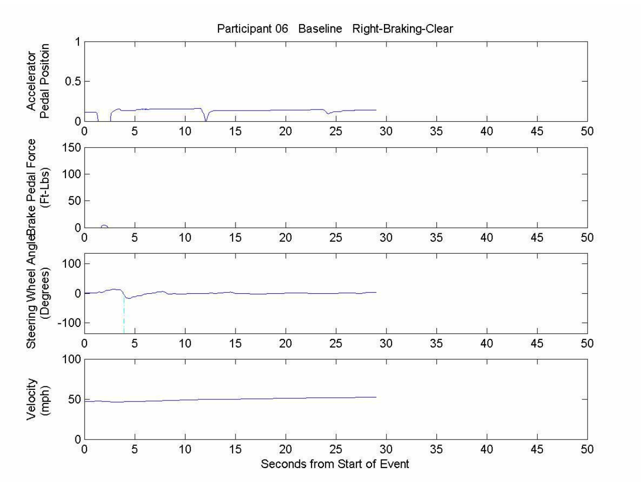


**Figure 12. Driver response to a braking lead vehicle in the form of changing lanes to the right without slowing.**

Although slowing in response to the actions of the lead vehicle was a common response, not all participants responded in that manner. Some participants would change lanes at speed without slowing down. Figures 12 and 13 illustrate lane changes to the right and left, respectively, without any application of the brakes by the driver.

Another response, although even less common, was that the driver would make multiple lane changes during the event. Figure 14 provides an example of this type of response. As can be seen in the figure, in this case the participant changed lanes to the right without slowing and then changed lanes back to the left after negotiating around the braking lead vehicle.

Another outcome was a collision with the vehicle in the adjacent lane. Figure 15 illustrates a typical situation where the driver changes lanes to avoid colliding with the lead vehicle, but does not see the vehicle in the blind spot. As a result the participant cuts off the driver and a collision results.

At the time of publication of this paper, data collection has been completed only for participants in the age group $\leq 21$. Therefore the results presented

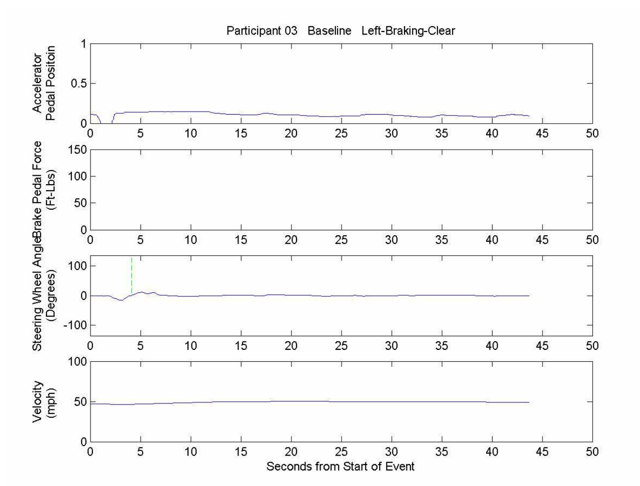


**Figure 13. Driver response to a braking lead vehicle in the form of changing lanes to the left without slowing.**

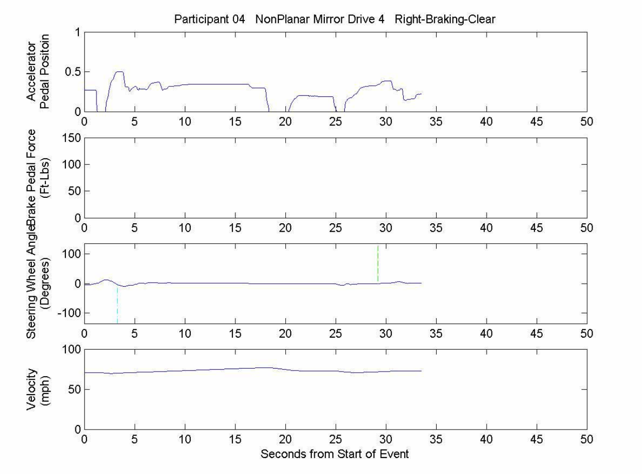


**Figure 14. Driver response to a braking lead vehicle in the form of changing lanes to the right and then back to the left without slowing.**

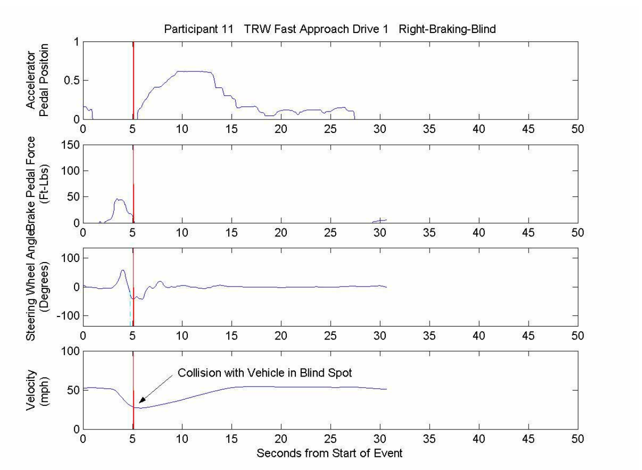


**Figure 15. Driver collides with vehicle in blind spot while responding to a braking lead vehicle.**

here are preliminary and will be expanded to include the > 65 age category in the final report of this study.

## CONCLUSIONS

From the preliminary results presented here, drivers in this study with an age of $\leq$ 21 when confronted with either a lead vehicle braking or an uncovered slower lead vehicle scenario, had one of two typical responses: 1) braking followed by a lane change or, 2) driver changes lanes by entering into the gap between vehicles in the adjacent lane and crashes into another vehicle. The first outcome was the more common and this result was not expected for drivers in this age group. The outcome that resulted in a crash was rare and occurred as a consequence of the driver changing lanes to avoid colliding with the lead vehicle, but did not see (or notice) the vehicle in the blind spot.

Additional analysis needs to be conducted to establish the limitations to their effectiveness and whether drivers will heed their warnings. A complete analysis will be presented in the final report at the completion of this study.

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